$W + 2$ *jets at the Tevatron*

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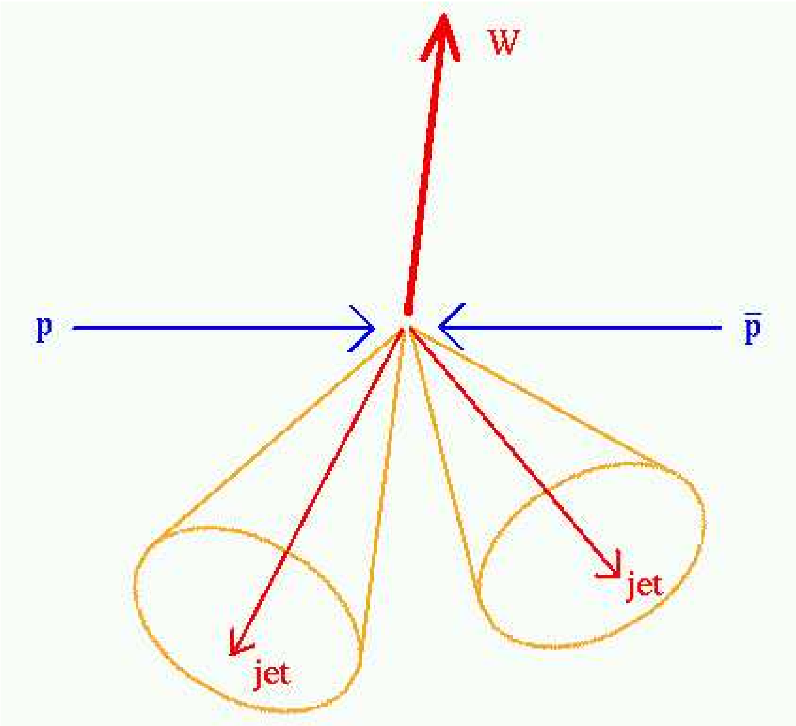
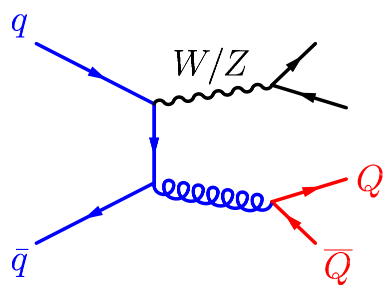
W +2 *jet events*

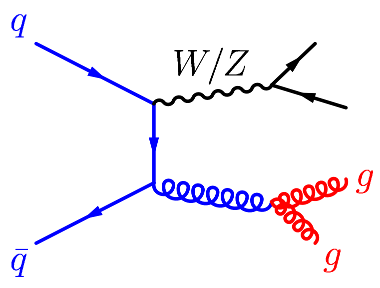
- Many such events at Run I of the Tevatron. For example, with an integrated luminosity of $108\ \mathrm{pb}^{-1}$ CDF collected $51400\ W \to e\nu$ events, of which 2000 are $W + 2$ jet events. This yields an $80\mathrm{pb}$ cross-section.



W +2 jet theory

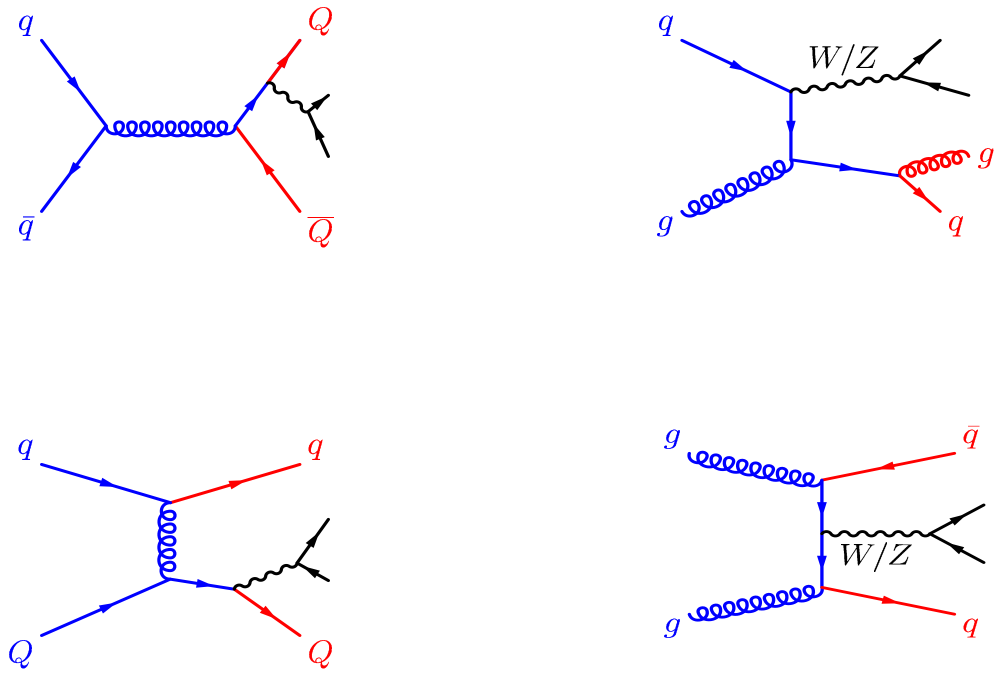
- In the leading order of perturbative QCD, this process can be represented by Feynman tree-graphs.
- At leading order a jet is represented by a single final state quark or gluon (Local Parton-Hadron Duality).
- There are two classes of diagrams at leading order, 4 quark and 2 quark, 2 gluon.





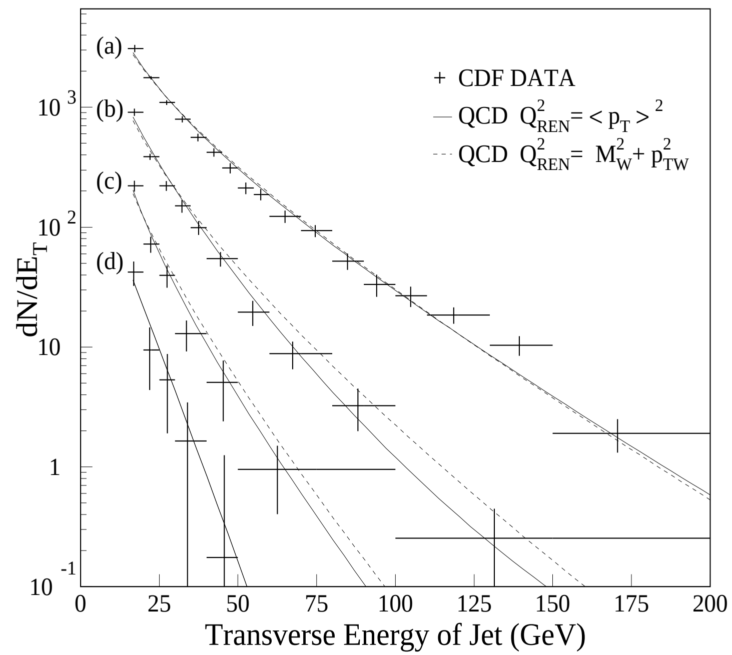
W +2 jet theory, continued

- Related diagrams provide other initial states that also contribute:



Multi-jet data

- This theory describes multi-jet data fairly well. For example, the leading-jet E_T spectrum for $W + n$ jet production ($n = 1, \ldots, 4$):



- Deficiency at high E_T in the $W + 1$ jet sample.

Failings of leading order

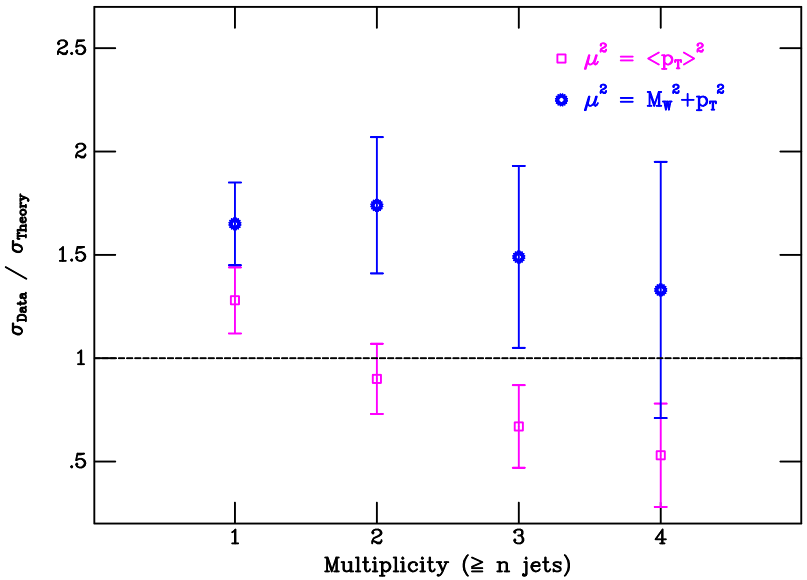
- Some discrepancies arise when the theory is examined in more detail.
- An important theoretical input is the value of the renormalization and factorization scales, μ_R and μ_F.
- These artificial variables are required only because we cannot solve the full theory of QCD. Instead, we compute an observable $\mathcal{O}_{\rm full}$ perturbatively,

$$\mathcal{O}_{\rm full}^{\rm W+2\ jet} = \alpha_S^2\, \mathcal{O}_2 + \alpha_S^3\, \mathcal{O}_3 + \ldots + \alpha_S^r\, \mathcal{O}_r + \ldots$$

- Truncating this series produces a dependence upon μ_R and μ_F in our predictions.
- Our leading order picture $= \mathcal{O}_2$.

Scale worries

- $W+ \geq n$ jets cross-sections from CDF Run I, compared with (enhanced) leading order theory:

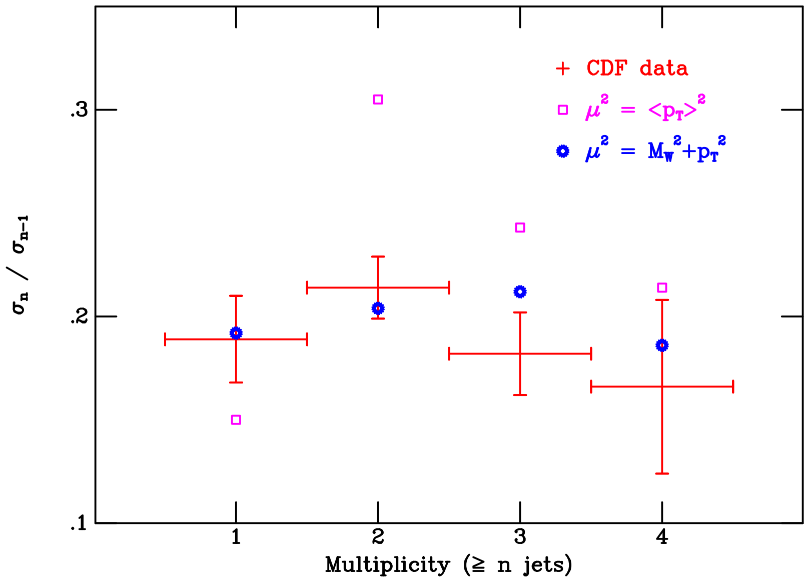


$$\mu_R = \mu_F \equiv \mu$$

- To reproduce the raw cross-sections, especially for the $W + 1, 2$ jet data, the low scale $\mu^2 = \langle p_T \rangle^2$ is preferred.

Scale worries, continued

- Ratio of n-jet cross sections, σ_n/σ_{n-1}:



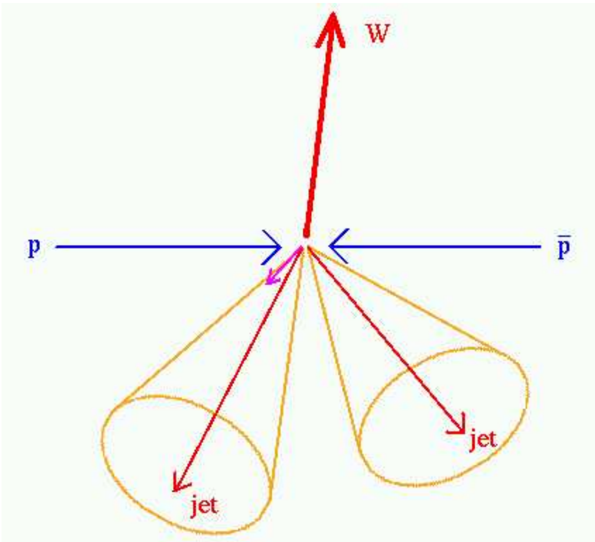
$$\mu_R = \mu_F \equiv \mu$$

- Measures the “reduction in cross section caused by adding a jet” (roughly $\sim \alpha_S$).
- Useful quantity since some systematics should cancel.
- High scale $\mu^2 = M_W^2 + p_T^2$ now much closer to data.

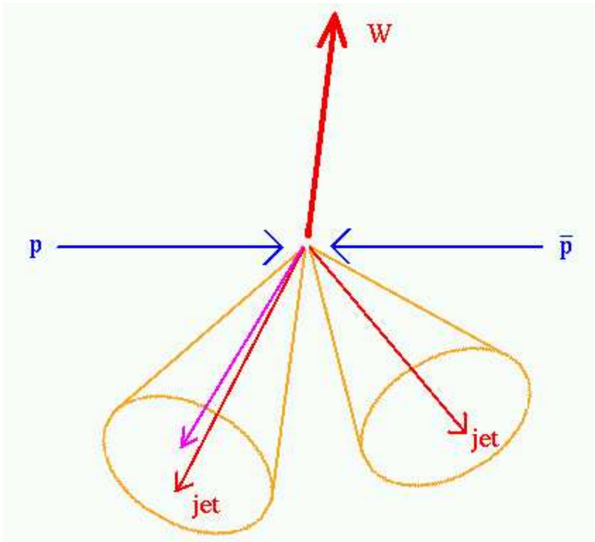
Next-to-leading order

- At next-to-leading order, we include an extra "unresolved" parton in the final state

soft



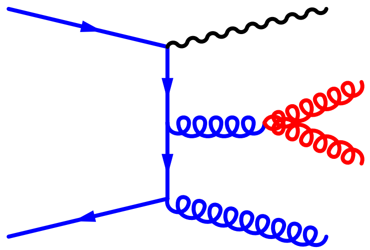
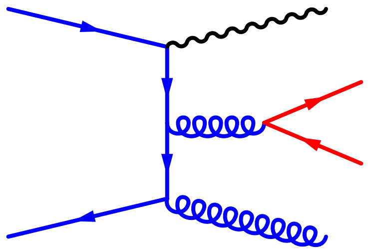
collinear



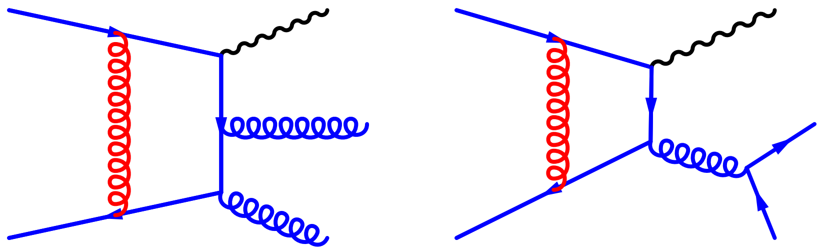
- The theory begins to look more like an experimental jet, so one expects a better agreement with data.

$W + 2$ *jets, NLO theory*

- Feynman diagrams for extra parton radiation, e.g.

soft gluon   collinear quarks

- Loop diagrams, also one extra factor of α_S:

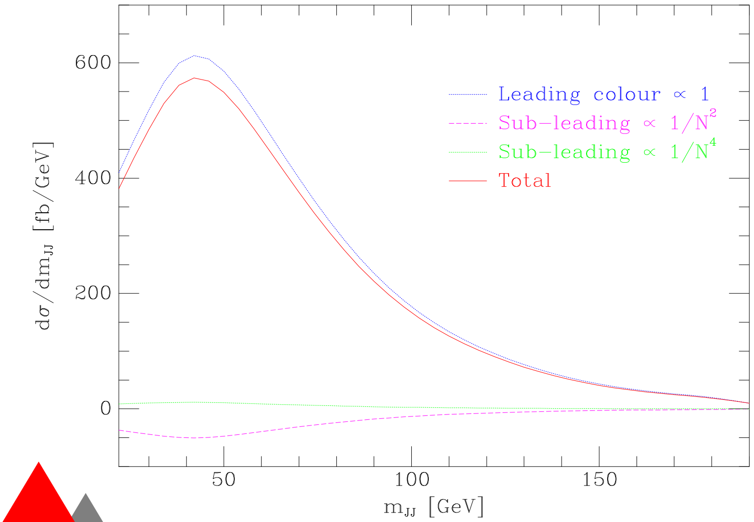


NLO difficulties

- There are two types of diagrams, each with a different number of final state partons.
- Theoretical procedure for combining these is well understood, but it does raise problems:
  - There is no longer a simple correspondence between a data event and the theory description.
  - No chance of interfacing with Pythia, since the first stage of the jet evolution is already included (some work in this area at present).
  - Less familiarity with NLO generators in general.

Colour decomposition

- Recall the two classes of diagrams - ones involving 2 quarks, 2 gluons and those with 4 quarks. We can write the matrix elements for these diagrams as an expansion in the number of colours, N.
- The 2 quark, 2 gluon diagrams contain the leading term and pieces suppressed by $1/N^2$ and $1/N^4$. The 4 quark diagrams are suppressed by $1/N$ and $1/N^3$.



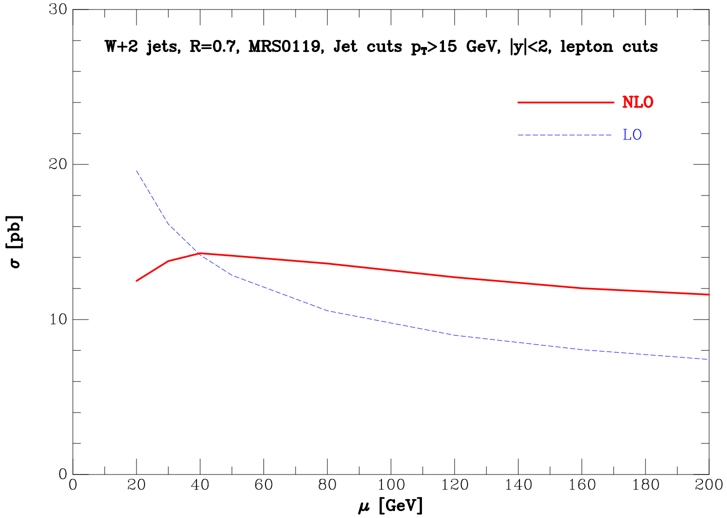
dijet mass distribution

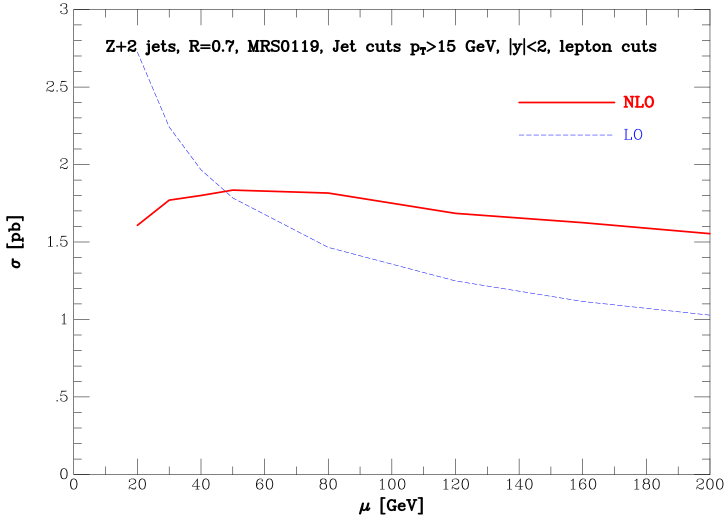
Event cuts

- k_T clustering algorithm with pseudo-cone size, $R = 0.7$.
- Jet cuts:
  $p_T^{\mathrm{jet}} > 15$ GeV, $|y^{\mathrm{jet}}| < 2$.
- Exclusive cross-section - so exactly 2 jets.
- Lepton cuts:
  $p_T^{\mathrm{lepton}} > 20$ GeV, $|y^{\mathrm{lepton}}| < 1$.
- (W only) Missing transverse momentum:
  $p_T^{\mathrm{miss}} > 20$ GeV.
- (Z only) Dilepton mass:
  $m_{e^-e^+} > 15$ GeV (since γ^* is also included).

Scale dependence

- Choose equal factorization and renormalization scales.
- Examine scale dependence of the cross-section integrated over 20 GeV $< m_{JJ} < 200$ GeV.

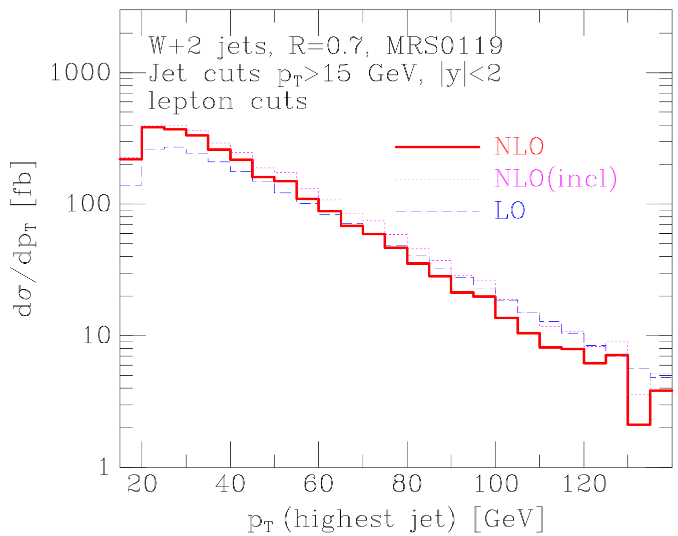


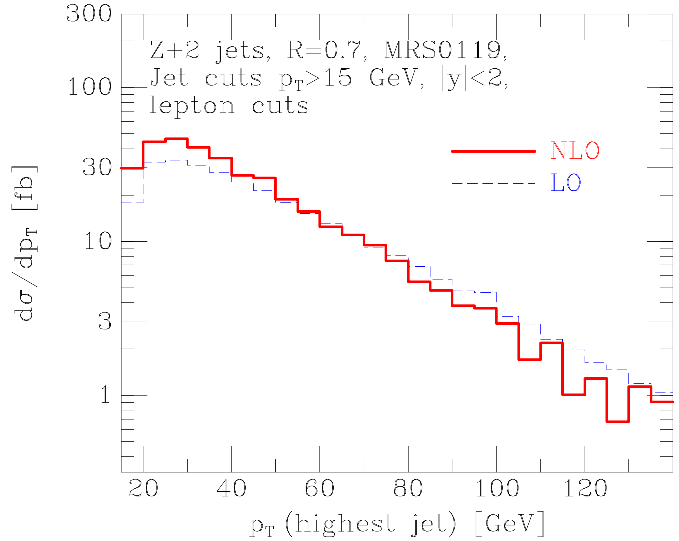


- Scale dependence much reduced from $\sim 100\%$ to $\sim 10\%$ in both cases.

Leading p_T distribution

- p_T distribution of the hardest jet in $W, Z{+}2$ jet events, at the scale $\mu = 80$ GeV.





- Turn-over at low p_T since 15 GeV $< p_T^2 < p_T^1$.
- The exclusive spectrum is much softer at next-to-leading order, as in the 1-jet case.
- High-E_T tail is ‘filled in’ for the inclusive case.

Heavy flavour content

- Many signals of new physics involve the production of a W or Z boson in association with a heavy particle that predominantly decays into a $b\bar{b}$ pair.
- A light Higgs is a prime example and will provide a promising search channel in Run II.

$$p\bar{p} \longrightarrow W(\rightarrow e\nu)H(\rightarrow b\bar{b})$$

$$p\bar{p} \longrightarrow Z(\rightarrow \nu\bar{\nu}, \ell\bar{\ell})H(\rightarrow b\bar{b})$$

- However, we will need to understand our SM backgrounds very well to perform this search.
- The largest background is 'direct' production:

$$p\bar{p} \longrightarrow W\, g^{\star}(\rightarrow b\bar{b})$$

$$p\bar{p} \longrightarrow Z\, b\bar{b}$$

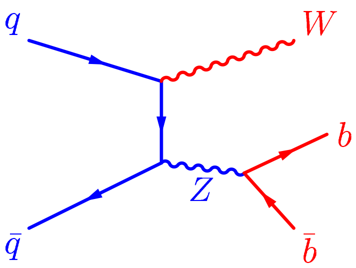
MCFM Summary - v. 3.0

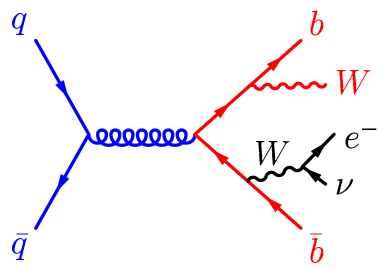
$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm/Z + H$	$p\bar{p} \to W^\pm/Z + 1$ jet
$p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W + 2$ jets	$p\bar{p} \to Z + 2$ jets

- MCFM aims to provide a unified description of a number of processes at NLO accuracy.
- Various leptonic and/or hadronic decays of the bosons are included as further sub-processes.
- MCFM version 2.0 is now part of the CDF code repository. Working with D. Waters et al. to produce user-friendly input and output, e.g. event ntuples, event generator interface.

Other $Wb\bar{b}$ backgrounds

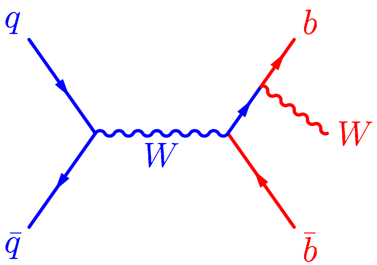
diboson

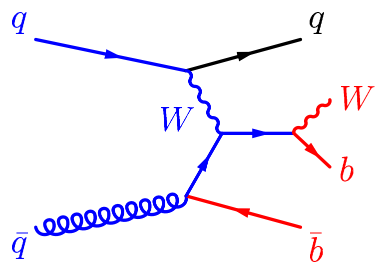




$t\bar{t}$

single top (s)

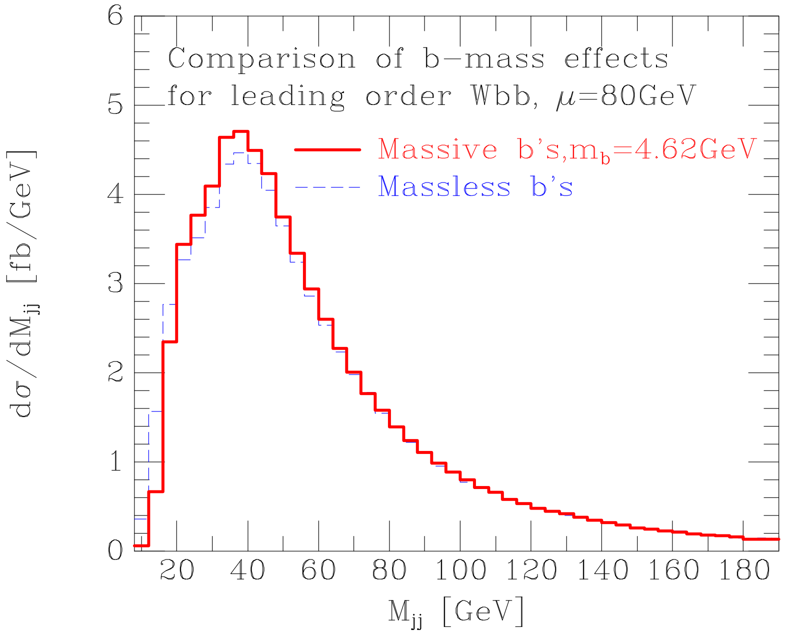


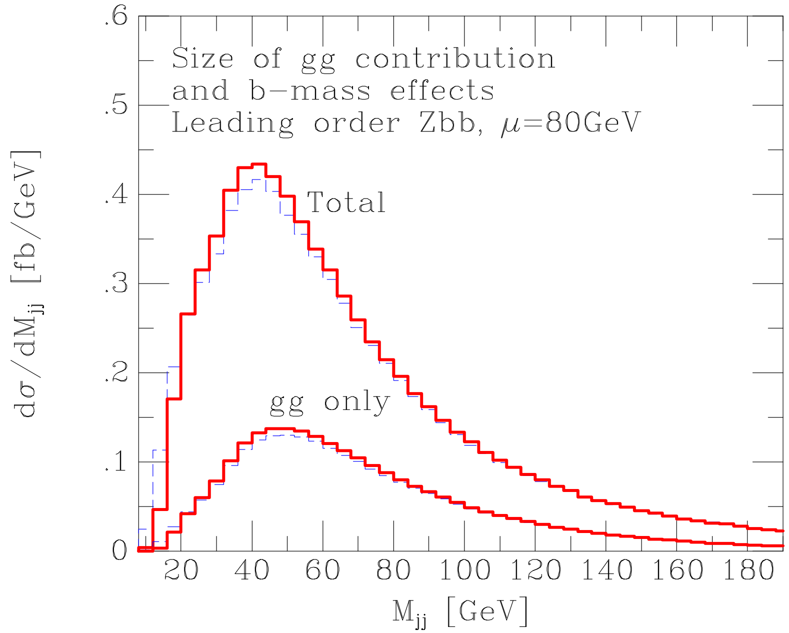


single top (t)

b-mass effects

- Compare the lowest order predictions for m_b zero and non-zero.

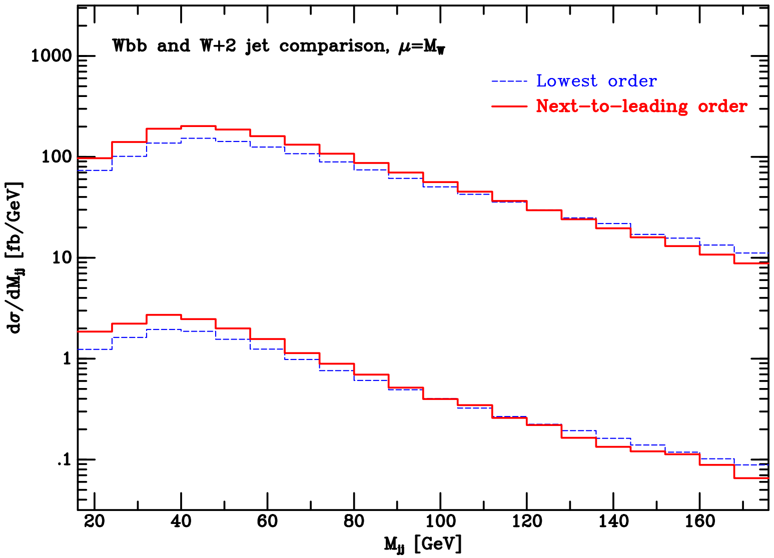


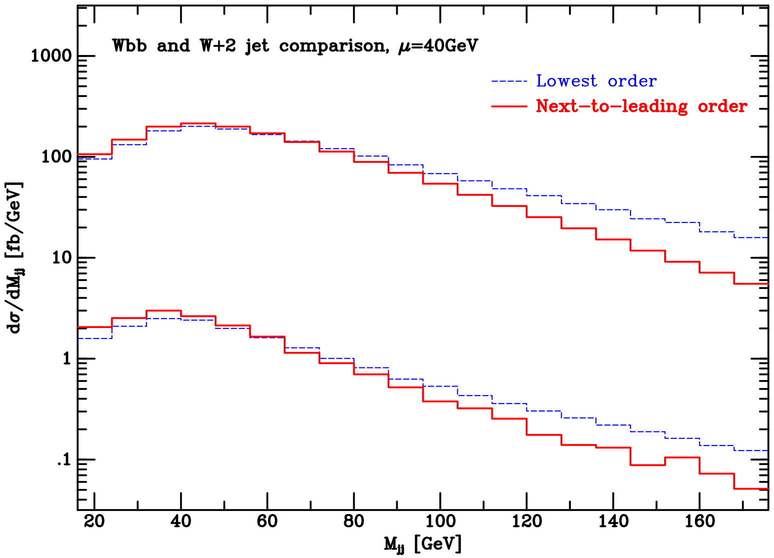


- In the interesting region - the peak at low mass - matrix element effects dominate over phase space. The corrections there are of order 5%.

m_{JJ} distributions

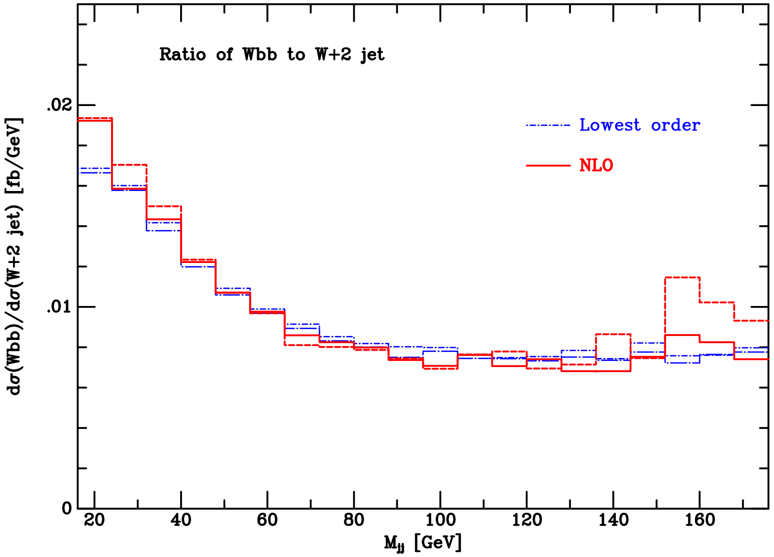
- $Wb\bar{b}$ and $W+2$ jet distributions appear very similar in shape at both LO and NLO. The shapes change when moving to a lower scale, with a depletion in the cross-section at high M_{jj}.





Heavy flavour fraction

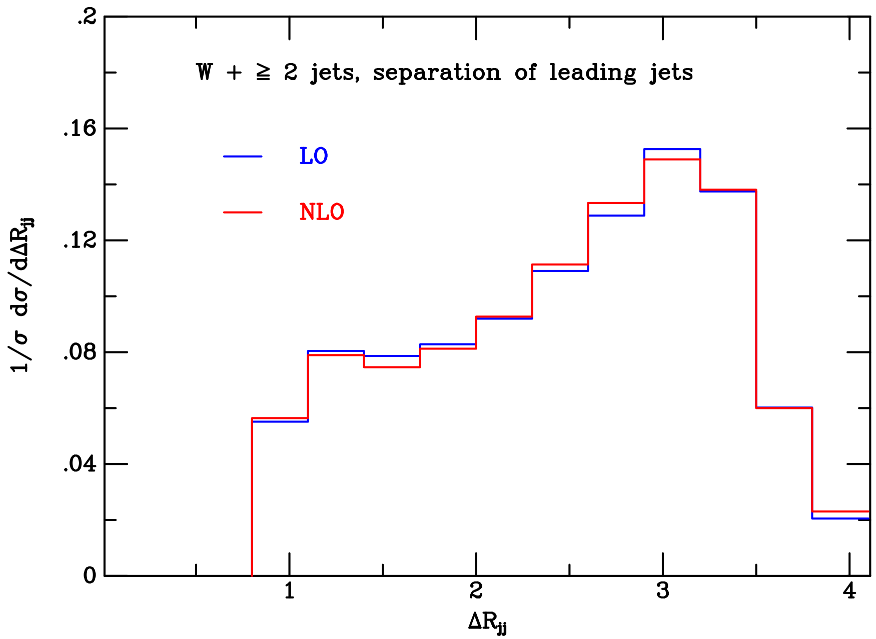
- The ratio of b-tagged to untagged jets changes very little at NLO and appears to be predicted very well by perturbation theory.



- The fraction is peaked at low M_{jj}, where it is approximately 2.5 times as high as the fairly constant value of 0.8% for $M_{jj} > 60$ GeV.

Jet-jet separation

- In Run I, there was some discrepancy in the shape of the jet-jet separation ΔR_{jj} compared with LO theory.
- Results at NLO appear to confirm the leading order shape, with no significant dependence on scale.



Summary

- The NLO corrections for $W/Z+2$ jets have been calculated.
- Scale dependence is greatly reduced to $\sim 10\%$ and distributions are considerably changed upon including QCD corrections.
- NLO code is contained in MCFM v3.0. Current code in the CDF repository is v2.0 and will be updated soon.
- The fraction of a $W+2$ jet sample that contains two b-jets is predicted very well in perturbation theory.
- Some experimental collaboration needed to determine interesting observables to predict.